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(71) Applicant : International Business Machines
Corporation
Old Orchard Road
Armonk, N.Y. 10504 (US)

(72) Inventor : Fukuzawa, Tadashi
3-23-2 Kyodo, Setagaya-ku
Tokyo-to (JP)

Inventor : Kano, Satoru S.
201, 998-1, Futo, Kohoku-ku
Yokohama, Kanagawa-ken (JP)
Inventor : Kumata, Kiyoshi
Rm. No. 201 Kiku Heim, 7-9 Hongo 5-chome
Bunkyo-ku, Tokyo-to (JP)
Inventor : Lee, Victor Y.
1160 Quail Ridge Court
San Jose, CA 95120 (US)
Inventor : Schellenberg, Franklin Mark
10162-B Alpine Dr.
Cupertino, CA 95014 (US)
Inventor : Takahashi, Yutaka
3-9-22 Tsurumaki, Setagaya-ku
Tokyo-to (JP)

(74) Representative : Atchley, Martin John
Waldegrave
IBM United Kingdom Limited Intellectual
Property Department Hursley Park
Winchester Hampshire SO21 2JN (GB)

(54) Nonlinear optical device and method of manufacturing.

(57) The invention relates to a nonlinear optical device comprising a film structure (2) coated on a substrate (1) without interposition of adhesive.

According to the invention the device is characterised in that the film structure comprises a modulated intercalation structure consisting of a layer of semi-conductor material and a layer of organic material, the layers having different energy gaps and the modulated structure being a super lattice structure.

The invention also relates to a method of manufacturing a nonlinear optical device comprising dissolving an organic material in a solvent, and spin coating the solution onto a substrate and thereby forming an organic material film with one of its crystal axes oriented in the direction normal to the substrate, the film having a modulated structure of the two types of layers alternately intercalated and differing in energy gap in the direction.

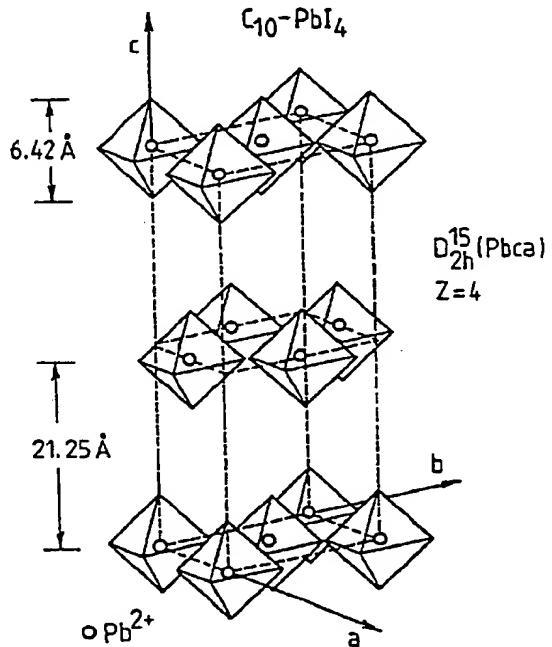


FIG. 6

Jouve, 18, rue Saint-Denis, 75001 PARIS

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NONLINEAR OPTICAL DEVICE AND METHOD OF MANUFACTURING

This invention relates to a nonlinear optical device for use in optical data processing apparatus or optical communication apparatus in which the device is controlled by external optical or electrical signals, and to a method of manufacturing such a device.

The third-order nonlinear optical coefficient $\chi^{(3)}$ is the key parameter for evaluating materials to be used in nonlinear optical devices. Both real and imaginary parts of the refractive index significantly change with the light intensity only when $\chi^{(3)}$ is sufficiently large. Optical devices which are to be controlled by an external light or electrical field must have a large $\chi^{(3)}$ for practical application.

Some classes of semiconductor are known to have large $\chi^{(3)}$ and can be integrated with conventional semiconductor optical devices.

The literature concerning these techniques includes the following :

- (1) S. Y. Yuen and P. A. Wolff : Technical Digest, pp. 150-153 of Nonlinear Optical Properties of Materials Topical Meeting ; August, 1988, Troy, New York.
- (2) D. A. B. Miller, C. T. Seaton, M. E. Price, and S. D. Smith : Phys. Rev. Lett. 47, 197 (1981).
- (3) C. K. N. Patel, R. E. Slusher, and P. A. Fleury: Phys. Rev. Lett. 17, 1011-1017 (1966).
- (4) D. A. B. Miller, D. S. Chemla, D. J. Eilenberger, P. W. Smith, A. G. Gossard, and W. Wiegmann : Appl. Phys. Lett., 42, 925 (1983).
- (5) H. M. Gibbs, S. S. Tamg, J. L. Jewell, D. A. Weinberger, and K. Tai : Appl. Phys. Lett., 41, 221-222 (1982).
- (6) A. Honold, L. Schultheis, J. Kuhl, and C. W. Tu : Technical Digest of 16th International Conf. on Quantum Electronics, Tokyo (1988).
- (7) T. Ishihara, J. Takahashi, and T. Goto : Solid State Communication, 69, 933 (1989).
- (8) E. Hanamura : Nato workshop on "Optical Switching in Low-dimensional Systems," October (1988), Marbella, Spain.
- (9) Yu. I. Dolzhenko, T. Inaba and Y. Maruyama: Bull. Chem. Soc Japan, 59, 563 (1986).

In a narrow-band-gap semiconductor, band filling (Ref. 2) and nonparabolicity of the conduction band (Ref. 3) cause extremely large nonlinearity (e. g., $\chi^{(3)} = 3 \times 10^{-1}$ esu for a single InSb crystal). For practical use, however, because the nonlinearity is significant at longer wavelengths (5 μm to 10 μm), this class of semiconductor will not be employed in optical data processing apparatus.

It is desirable to find other mechanisms for achieving large $\chi^{(3)}$ at shorter wavelengths for higher packing density of the optical device. The excitonic transition of semiconductor quantum wells is very promising (Refs. 4, 5). The large $\chi^{(3)}$ comes from satu-

ration absorption at exciton resonances. Since the contribution of excitonic transitions (compared to that of inter-band transition) is larger when the band gap is wide, this mechanism is more favourable at shorter wavelengths. The excitonic process giving rise to large $\chi^{(3)}$ is common to bulk crystal systems, but the excitonic transition of a modulated structure or quantum well system (hereafter the former is included in the latter) is more significant because of the enhancement by the quantum confinement effect.

Although this system is far better than bulk crystal systems, it has still several problems to be solved from practical viewpoints.

15) The exciton binding energy in a quantum well is still low (around 10 meV). Therefore, phonons at room temperature decrease the number of excitons, and it is necessary to operate the device below the temperature of liquid nitrogen to obtain strong absorption.

20) The system response time is long because of the long lifetime of the free carrier, and therefore a fast device will be hard to obtain.

25) Manufacturing the semiconductor quantum well requires expensive equipment and complicated manufacturing processes such as molecular beam epitaxy (MBE) and metal organic chemical vapour deposition (MOCVD).

30) It is still not possible to make an ideal quantum well with completely flat structure on the atomic scale. A fluctuation in the epitaxial growth process causes irregularity in the size of the quantum well. An exciton lifetime of 2.8 ps is expected for the ideal quantum well system, while 180 ps has been observed for an actual system (Ref. 6).

35) The object of the present invention is to provide an improved nonlinear optical device and a method of manufacturing such a device.

The invention relates to a nonlinear optical device comprising a film structure coated on a substrate without interposition of adhesive.

40) According to the invention the device is characterised in that the film structure comprises a modulated intercalation structure consisting of a layer of semi-conductor material and a layer of organic material, the layers having different energy gaps and the modulated structure being a super lattice structure.

45) The invention also relates to a method of manufacturing a nonlinear optical device comprising dissolving an organic material in a solvent, and spin coating the solution onto a substrate and thereby forming an organic material film with one of its crystal axes oriented in the direction normal to the substrate, the film having a modulated structure of the two types of layers alternately intercalated and differing in energy gap in the direction.

In order that the invention may be more readily understood embodiments will now be described with reference to the accompanying drawings, in which :

Figures 1, 2, 3, 4, and 5 are sectional views respectively showing the structures of different embodiments of optical devices according to the invention,

Figure 6 is a crystal structure model depicting the single-crystal structure of $(C_5H_{11}NH_3)_2PbI_4$ used according to the invention,

Figure 7 is a graph showing the result of measurements taken on the formed film by means of a WYKO interferometry system,

Figure 8 is a graph showing the X-ray diffraction distribution of the film formed,

Figure 9 is a graph showing the absorption spectra obtained respectively from the thin film of this invention and from a single crystal, and

Figures 10 and 11 are graphs representing the bistable characteristics of different embodiments of the invention.

In order to obtain a large $\chi^{(3)}$ with a fast response time, it is desirable to use a multi-quantum-well system for a semiconductor, without any irregularity in the well structure. A two-dimensional perovskite semiconductor crystal, $(C_{10}H_{21}NH_3)_2PbI_4$, which is used in the stage of an intercalation of the semiconductor layer and an organic material layer, is to be used. The crystal structure of $(C_{10}H_{21}NH_3)_2PbI_4$ is shown in Figure 6. As shown in this figure, each mono-layer consisting of Pb^{2+} and I is sandwiched between two layers of alkyl-NH₃. The N atom, which is adjacent to the Pb^{2+} ion, forms a ligand field, thereby determining the wavelength of the optical transition of Pb^{2+} . What has been described above is an ideal quantum well structure in the form of intercalation of a semiconductor and an organic material and having a constant well thickness of 6.24 Å (6.24×10^{-10} m) throughout the crystals. Moreover, the binding energy of the exciton in this quantum well is quite large : the observed value is 370 meV (which is twelve times as large as that of the bulk crystal of PbI₂), and thus one can observe a strong absorption peak even at room temperature, as shown at (a) in Figure 9.

The two-dimensional perovskite semiconductor crystal looks extremely promising as a non-linear optical device. However, the problem lies in the difficulty of making a large enough crystal for device application, if we use the crystal growth method reported so far (Ref. 9). It takes one to two months to obtain a single crystal of $2 \times 2 \times 0.1$ mm³ by the silica-gel technique. Another problem is the difficulty in controlling the crystal size (especially the crystal thickness) when we use this technique.

A novel epitaxial technology for making a thin optical film of two-dimensional perovskite on a transparent substrate will now be described. This technology is essential for realisation of non-linear optical

data-processing devices. Thus, it provides a non-linear optical component with high optical quality, which affords an ultra-fast response time and high nonlinear optical sensitivity.

5

Embodiment 1

(a) Synthesis of $(C_{10}H_{21}NH_3)_2PbI_4$

In a flask, 9.5 g of lead acetate was suspended in 150 ml of distilled water. 2.86 ml of glacial acetic acid was added and stirred. Then 10 ml of decyl amine was added and stirred for 10 minutes. A solution of 16.6 g of potassium iodide in 100 ml distilled water was added to the above mixture and stirred. A thick orange suspension formed was filtered off and washed with water. The obtained crystals were dried under a vacuum. The product was recrystallised in nitromethane to give a thin golden platelet.

(b) Spin coating of $(C_{10}H_{21}NH_3)_2PbI_4$

A 5 wt% solution of $(C_{10}H_{21}NH_3)_2PbI_4$ in acetone was spin-coated on a one-inch diameter quartz disc (1 in Figure 1). The spinning speed was 2000 rpm.

(c) Evaluation of the film

An optically flat thin film 2 of $(C_{10}H_{21}NH_3)_2PbI_4$ was formed, as shown in Figure 1. The thickness and smoothness of the film were measured by a WYKO interferometry system. The result is shown in Figure 7. Thus an optically flat thin film having 100 nm thickness and less than $\lambda/100$ surface roughness was obtained except for the edge of the substrate.

The crystal structure of the film was evaluated by X-ray diffraction measurement. The X-ray diffraction intensity is plotted against the diffraction angle in Figure 8. The figure shows the existence of quite a good periodicity for 21.3 Å (21.3×10^{-10} m), which is the distance of separation of the two-dimensional Pb layers of the crystal along the c axis (Figure 6). This result implies that each plane of PbI₄, which is a quantum well, is stacked up with the distance of 21.25 Å (21.3×10^{-10} m), as in a crystal, to form a multi-quantum-well structure along the substrate surface. The film is not necessarily a single crystal, although no crystallinity in the direction of the a and b axes could be detected. However, even where a single crystal of $(C_{10}H_{21}NH_3)_2PbI_4$ itself is concerned, the quantum confinement mechanism depends solely on the well structure along the c axis ; therefore, the optical property based on this mechanism will be observed, even when it has the quantum well structure only in the direction of the c axis.

The absorption spectrum of a film (made from 5% solution) is shown at (b) in Figure 9. A strong peak around 2.42 eV, which is the exciton absorption in the PbI₄ quantum well, was observed as in the case of a single crystal ((a) in Figure 9)).

Observation with an optical microscope showed that there was no visible crystal domain structure in the thin-film layer. On the other hand, when a 10 wt%

solution of $(C_{10}H_{21}NH_3)_2PbI_4$ was used for spin coating, the thin film became opaque and many crystal domains were observed.

With conventional technology, it takes several months to grow most bulky single crystals of $2 \times 2 \times 0.1\text{ mm}^3$. With the technology described herein, powder crystals, which can be obtained in only half a day, are used to form an optical-quality thin-film crystal with a large active area on a substrate very quickly by spin coating. The technology of spin coating the thin film with the optical property described above has the potential to take the place of the hitherto used manufacturing methods, such as MBE and MOCVD processes, for which complex and costly equipment and sophisticated techniques are required.

Note that a suitable solvent of $(C_{10}H_{21}NH_3)_2PbI_4$, such as dimethoxyl ethane may be chosen as a solvent instead of acetone.

Embodiment 2

A different structure from that in Embodiment 1 is shown in Figure 2. The difference is in the incorporation of a waveguide layer 3. In this case, a 1- μm Corning 7059 glass layer was first sputtered on a quartz substrate. Then a 200-nm thin-film layer of $(C_{10}H_{21}NH_3)_2PbI_4$ was made by spin coating, which is similar to the method described in Embodiment 1. With this arrangement, photons having an energy of 2.4 eV along the thin film and 7059 glass layers are projected into the optical waveguide. For waveguide mode excitation, a prism coupler method was utilised. With the irradiation of the optical beam path in the waveguide by a light with 2.45-eV photon energy and 2-ps pulse width from the direction normal to the substrate, the light beam intensity of 2.4 eV was increased by 27 times. This optical modulation by light shows the ultra-high-speed response of $(C_{10}H_{21}NH_3)_2PbI_4$.

Embodiment 3

A multi-layered structure of $(C_{10}H_{21}NH_3)_2PbI_4$ layers and resist layers for lithography was made in this embodiment. In Figure 3, $(C_{10}H_{21}NH_3)_2PbI_4$ layers are denoted by the number 4 and poly-(di-n-hexylsilane) layers are denoted by the number 5. The thicknesses of these layers were 100 nm and 300 nm, respectively. The spin coating of the $(C_{10}H_{21}NH_3)_2PbI_4$ layer was done in the same way as in Embodiment 1. The high-molar-weight poly-(di-n-hexylsilane) layers were made by spin coating using a 2.5% solution in isoctane.

An optical modulation experiment was conducted with this structure. The wavelengths of the incident beam and control beam were the same as in Embodiment 2. In this case, the sample was irradiated by a parallel beam of normal incidence and also by the

controlling light beam at an incidence angle of 15°. For a series of optical image information processes, observation was made by a CCD TV camera from the direction opposite to that of the incident light beam array.

Embodiment 4

The quartz plate 1 with semi-transparent mirror 6 shown in Figure 4 was used as a substrate to be spin-coated. A thin film of $(C_{10}H_{21}NH_3)_2PbI_4$ formed thereon as in Embodiment 1. Then gold was vapour-deposited on the thin film as a semi-transparent mirror 7. Two mirrors 6 and 7 constitute an optical resonator (Figure 4). A light beam of 2.45-eV photon energy was introduced by normal incidence to the substrate. The light intensity after passing through the resonator had the optically bistable characteristic, as shown in Figure 10.

Embodiment 5

Other two-dimensional perovskites, $MX_4(C_nH_{2n+1}NH_3)_2$, were also synthesised and used as thin films. Here M represents a metal ion such as Cu, Cd, Mn or Fe, and X represents either a halide ion or an I, Cl, or Br ion. Alkyl-ammoniums with $n = 3, 5, 8$, and 10 of the mono-ammonium family, were used. In these perovskites, the periodicity originating from the quantum well structure of the spin-coated thin-film layer was observed.

Embodiment 6

A structure using $(C_6H_{11}NH_3)_2PbI_4$ as a two-dimensional perovskite that resembles that of Embodiment 4 is shown in Figure 5. A quartz disc with a semitransparent gold mirror 8 formed thereon was used as a substrate, as in Embodiment 4, but here, a thin film 9 was formed on the metal layer side of the substrate 1. Then, a half mirror 10 was formed on this surface. An optically bistable characteristic was obtained in this Embodiment as in Embodiment 4 (Figure 11).

As described above, the methods described herein make it possible to provide a quantum well mechanism without using a single-crystal manufacturing process, which is complex and time-consuming, thereby enabling a nonlinear optical device to be produced at low cost and by a simplified process.

Claims

1. A nonlinear optical device comprising a film structure (2) coated on a substrate (1) without interposition of adhesive characterised in that said film structure comprises

a modulated intercalation structure consisting of a layer of semi-conductor material and a layer of organic material said layers having different energy gaps and said modulated structure being a super lattice structure. 5

ing a film of $(C_{10}H_{21}NH_3)_2PbI_4$ with one of its crystal axes oriented normal to the substrate, the film thus formed having a modulated structure of two types of layers alternately intercalated, differing in energy gap in said direction.

2. A nonlinear optical device as claimed in Claim 1, wherein said film structure is an assembly solely of microcrystals, each of said microcrystals having a specified axis in the normal direction to said substrate, but randomly oriented axes in the parallel direction to said substrate. 10

3. A nonlinear optical device as claimed in Claim 1 or 2, wherein said film structure is $(C_{10}H_{21}NH_3)_2PbI_4$. 15

4. A nonlinear optical device as claimed in Claim 1 or 2, wherein said film structure is $MX_4(C_nH_{2n+1}NH_3)_2$ (where M denotes a metal ion that is one of Cu, Cd, Mn, Ge and Fe, and X a halogen ion that is one of I, Cl and Br). 20

5. A method of manufacturing a nonlinear optical device comprising dissolving an organic material in a solvent, and spin coating said solution onto a substrate and thereby forming an organic material film with one of its crystal axes oriented in the direction normal to said substrate, said film having a modulated structure of the two types of layers alternately intercalated and differing in energy gap in said direction. 25

6. A method of manufacturing a nonlinear optical device as claimed in Claim 5, wherein said organic material is $(C_{10}H_{21}NH_3)_2PbI_4$. 30

7. A method of manufacturing a nonlinear optical device as claimed in Claim 5, wherein said organic material is $MX_4(C_nH_{2n+1}NH_3)_2$ (where M denotes a metal ion that is one of Cu, Cd, Mn, Ge and Fe, and X a halogen ion that is one of I, Cl, and Br). 35

8. A method manufacturing of a nonlinear optical device as claimed in any one of Claims 5, 6 or 7, wherein said solvent is acetone. 40

9. A method of manufacturing a nonlinear optical device as claimed in any one of Claims 5, 6 or 7, wherein said solvent is dimethoxyl ethane. 45

10. A method of manufacturing a nonlinear optical device comprising preparing a solution of $(C_{10}H_{21}NH_3)_2PbI_4$ at a concentration lower than 10 wt% by dissolving $(C_{10}H_{21}NH_3)_2PbI_4$ in acetone, and then spin-coating said solution at a spin speed higher than 2,000 rpm, thereby form- 55

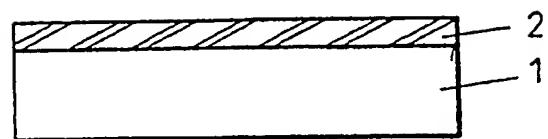


FIG. 1

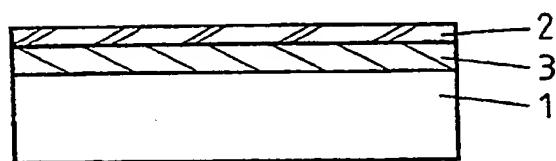


FIG. 2

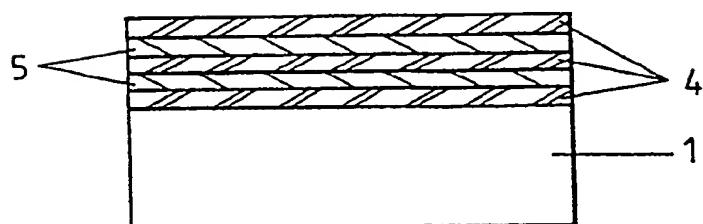


FIG. 3

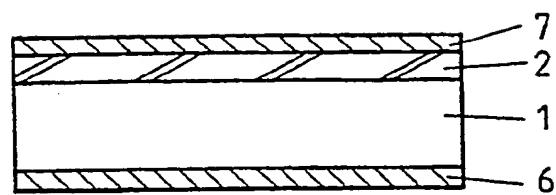


FIG. 4

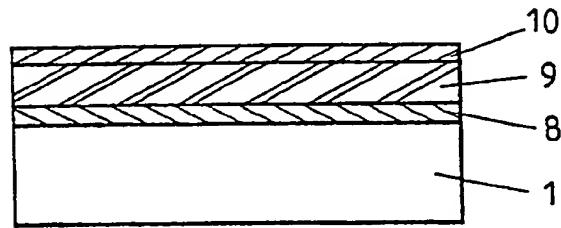


FIG. 5

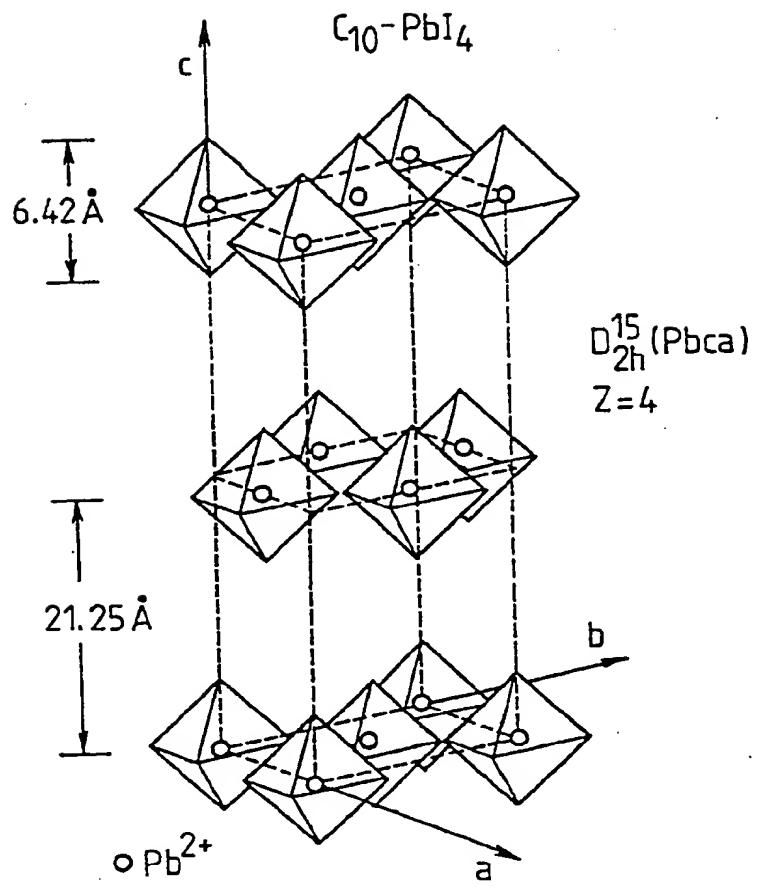


FIG. 6

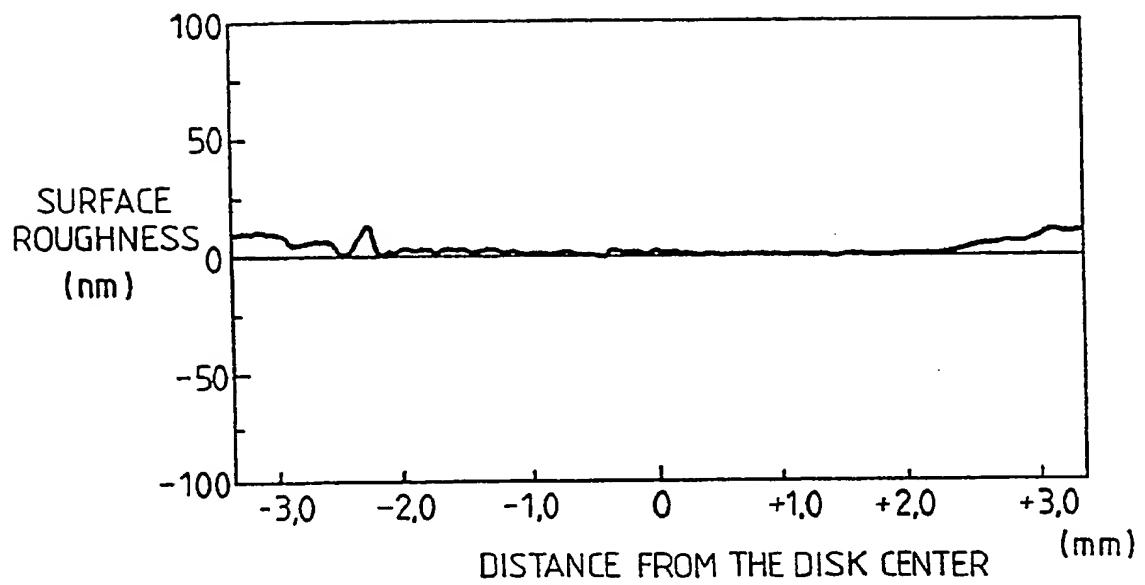


FIG. 7

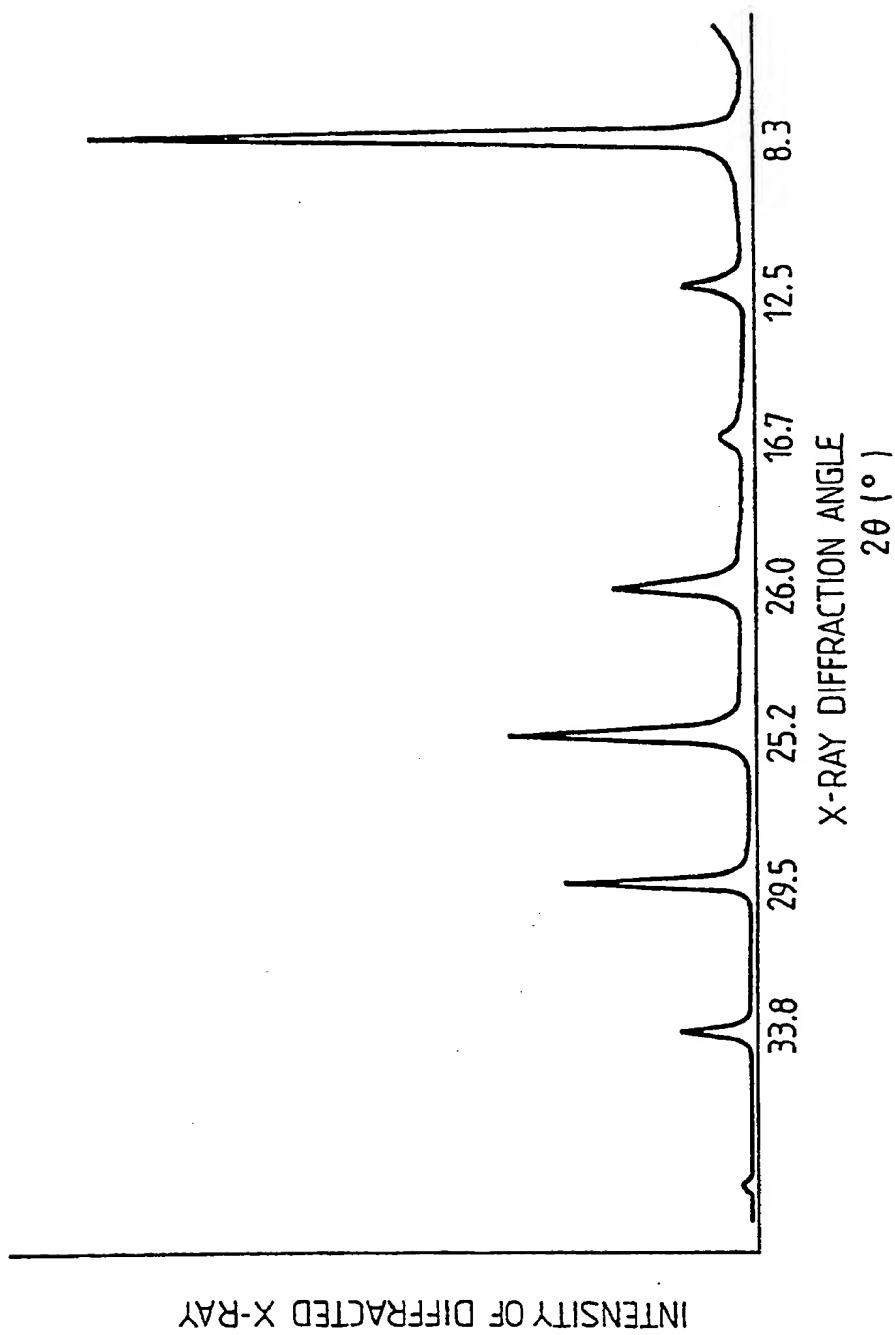


FIG. 8

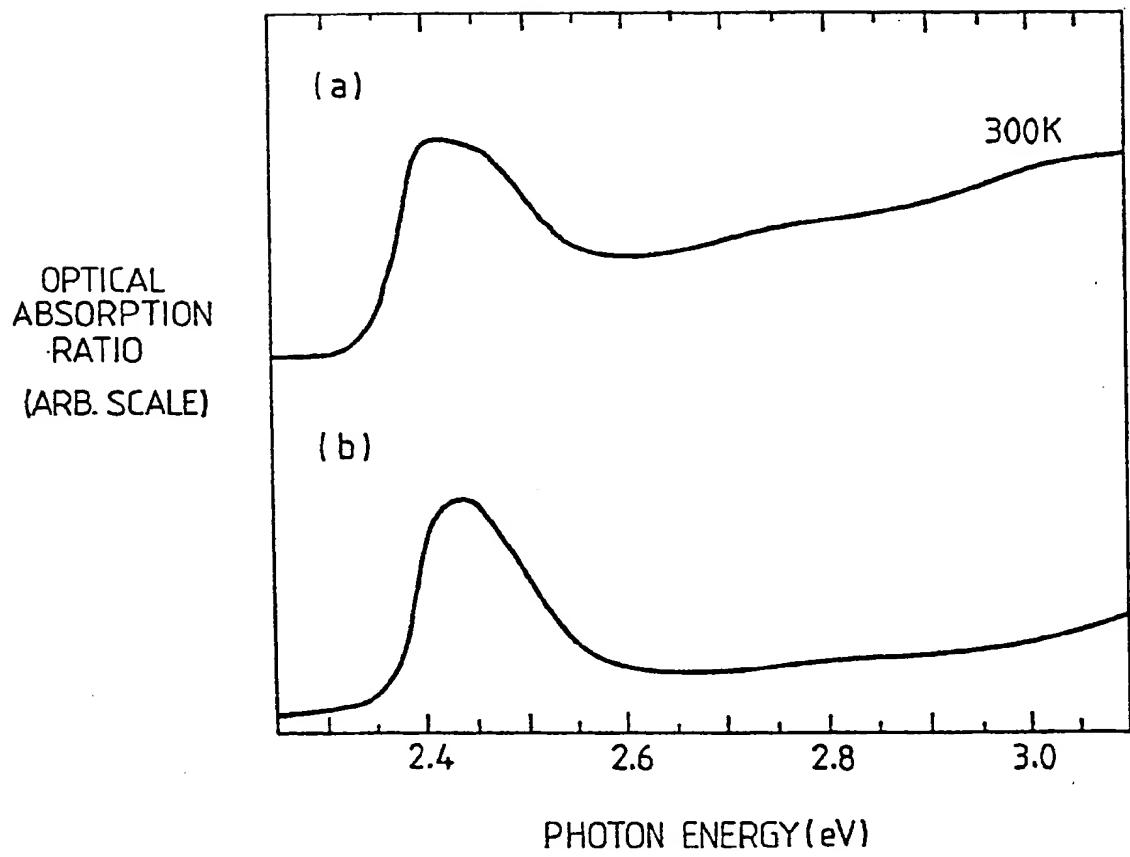


FIG. 9

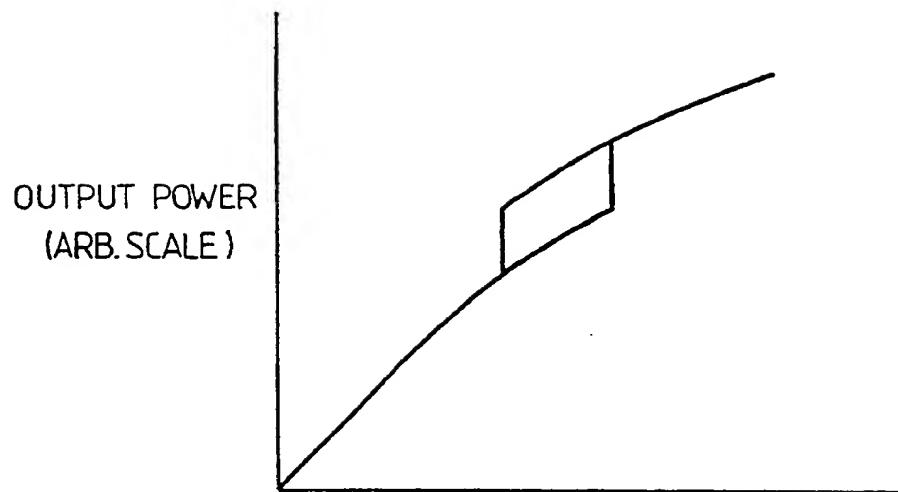


FIG. 10

INPUT POWER (ARB. SCALE)

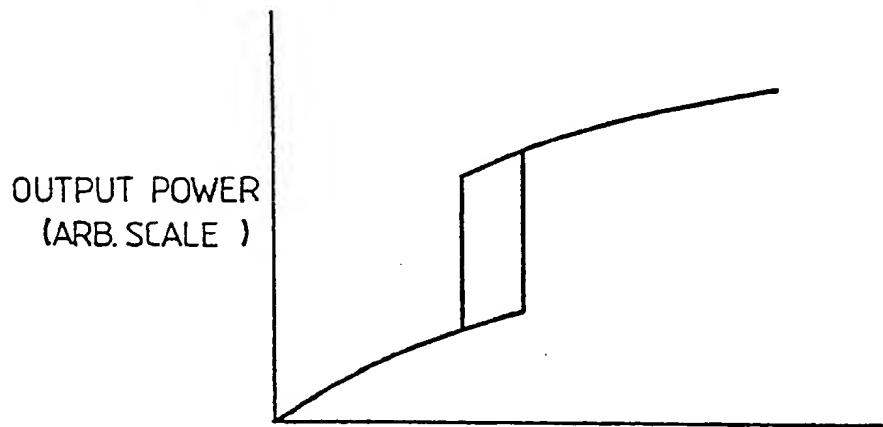


FIG. 11

INPUT POWER (ARB. SCALE)